Yrast 6^+ Seniority Isomers of ^{136,138}Sn

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Delayed γ-ray cascades, originating from the decay of (6^+) isomeric states, in the very neutron-rich, semimagic isotopes ^{136,138}Sn have been observed following the projectile fission of a ^{238}U beam at RIBF, RIKEN. The wave functions of these isomeric states are proposed to be predominantly a fully aligned pair of $f_{7/2}$ neutrons. Shell-model calculations, performed using a realistic effective interaction, reproduce well the energies of the excited states of these nuclei and the measured transition rates, with the exception of the $B(E2; 6^+ \to 4^+)$ rate of ^{136}Sn, which deviates from a simple seniority scheme. Empirically reducing the $\nu f^2_{7/2}$ orbit matrix elements produces a 4^+_1 state with almost equal seniority 2 and 4 components, correctly reproducing the experimental $B(E2; 6^+ \to 4^+)$ rate of ^{136}Sn. These data provide a key benchmark for shell-model interactions far from stability.

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The shell model plays a key role in allowing a microscopic description of many of the properties of atomic nuclei. In recent years, it has been shown that magic numbers present in stable nuclei can evolve as a function of isospin and new ones can emerge far from stability [1]. In order to correctly analyze the underlying mechanisms responsible for the modification of shell gaps and to describe the properties of nuclei in their vicinity, and beyond, reliable effective nucleon-nucleon (N-N) interactions are required. In recent years, much progress has been made in the theoretical derivations of realistic effective interactions, for example, using free N-N potentials and a so-called $V_{\text{low-}k}$ renormalization procedure [2] and the introduction of effective three-body forces to successfully reproduce experimental data [3]. However, the properties of the nuclear force at extreme values of isospin are not completely understood.

Some differences exist between experimental results and the predictions of modern effective interactions in nuclei beyond ^{132}Sn. For example, the low experimental $B(E2;0^+ \to 2^+)$ rate of ^{136}Te is not reproduced [4,5]. This has been proposed as being due to reduced neutron pairing beyond $N = 82$[6]. In order to scrutinize and optimize the neutron-neutron part of the effective interaction here, experimental data are required on the semimagic Sn isotopes beyond $N = 82$. The robust nature of the ^{132}Sn core means that low-energy states in very neutron-rich Sn isotopes just beyond $N = 82$ should consist of pure neutron excitations, offering a rare opportunity to examine the neutron-neutron components of effective N-N interactions in a very neutron-rich, heavy-mass region.

Currently, little is known about the Sn isotopes beyond $N = 82$, with only a few excited states reported in ^{133,134}Sn [7,8] and measured ground-state masses for ^{133,134,135}Sn [9]. In a basic seniority-2 ($\nu = 2$, 1 broken pair) scheme, the lowest-lying states of the semimagic ^{134,136,138}Sn are made up entirely of the $1f^2_{7/2}$ configurations [10]. The expected close proximity of pure 6^+_1 and 4^+_1 states should create an isomeric 6^+_1 state. Such an isomer has already been observed in ^{134}Sn [8]. Analogous 6^+ isomers are predicted to exist in ^{136,138}Sn [11–14], presenting an ideal opportunity to study excited states in these very exotic isotopes. Indeed, isomer spectroscopy of mass-identified fission fragments has often extended the boundaries of the most neutron-rich nuclei of the ^{132}Sn region with known excited states. More than 40 years ago, levels in the two-valence-proton nucleus ^{134}Te [15,16] were first identified this way. The advent of large-volume Ge detectors and improved beam intensities allowed nuclei with orders-of-magnitude weaker fission yields to be studied at the ILL [17] and at GSI [18]. The recent commissioning of the SRC cyclotron and BigRIPS spectrometer at RIBF, RIKEN, combined with the installation of the EURICA (Euroball-RIKEN Cluster Array) Ge γ-ray detector array, gives a unique opportunity to push the boundaries of spectroscopic studies to even more neutron-rich systems. The estimated production cross section for ^{138}Sn is 7 orders of magnitude smaller than that of ^{134}Te.

In this Letter, we report on measured γ-ray transition energies and rates in ^{136,138}Sn, providing a sensitive test of theoretical predictions far from stability for these simple semimagic nuclei.

The experiment was performed at the RIBF of the RIKEN Nishina Center. Neutron-rich Sn isotopes were produced following the projectile fission of a 345 MeV/u ^{238}U beam, impinging on a 3-mm thick Be target. The average primary beam intensity was about 8 pnA during 5 days of measurement time. The ions of interest were separated from other reaction products and identified on an ion-by-ion basis by the BigRIPS in-flight separator [19]. Particle identification was performed using the ΔE-ToF-$B\rho$ method in which the energy loss (ΔE), time of flight (ToF), and magnetic rigidity ($B\rho$) are measured and used to determine the atomic number Z and the mass-to-charge ratio (A/q) of the fragments. Details about this procedure can be found in Ref. [20]. An ion identification spectrum from the present experiment is shown in Fig. 1. In total, ~8.75×10^5 and ~5000 ions were identified for ^{136,138}Sn, respectively. The selected fragments were transported through the ZeroDegree spectrometer (ZDS) and finally implanted into the WAS3ABi (wide-range active silicon strip stopper array for β and ion detection) Si array positioned at the focal plane of the ZDS. The WAS3ABi detector [21] consists of eight double-sided silicon strip detectors (DSSSDs) with an area of 40×60 mm^2 and a thickness of 1 mm. The first four DSSSDs had segmentations of 40×60 strips each and the last four had 40×30 strips.

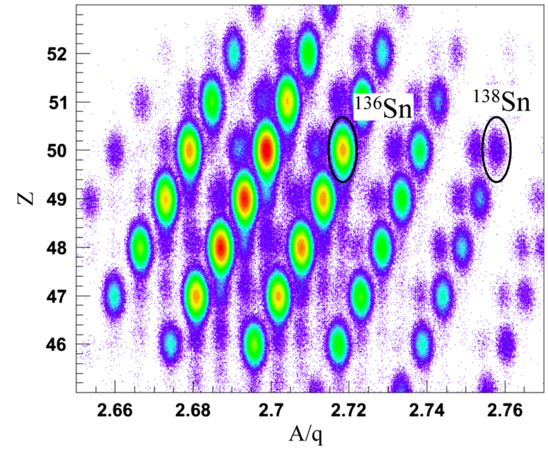

FIG. 1 (color online). Plot of nuclear charge Z versus mass-to-charge ratio A/q for ions produced, identified, and implanted into the WAS3ABi active stopper.

Following the fission reaction, some of the fragments are populated in an isomeric state. It is the aim of the present experiment to observe delayed γ rays emitted following the decay of isomeric states after their implantation in the DSSSDs. For this purpose, 12 large-volume Ge Cluster detectors [22], from the former EUROBALL spectrometer [23], were arranged in a close geometry around the WAS3ABi detector. The requirement of an ion-γ coincidence, in a time window of a few μs after the implantation of an ion, meant that delayed γ transitions could be unequivocally assigned to an isotope.

A spectrum of γ rays observed in delayed coincidence with identified and implanted ^{136}Sn ions is shown in Fig. 2(a). In this spectrum, three transitions are clearly seen with energies of 216, 391, and 688 keV. Since all of these transitions are observed in mutual coincidence, as shown in Fig. 3, they form a single cascade originating from one isomeric state. The inset of Fig. 2(a) shows the summed time spectra of all three transitions. A least-squares fit

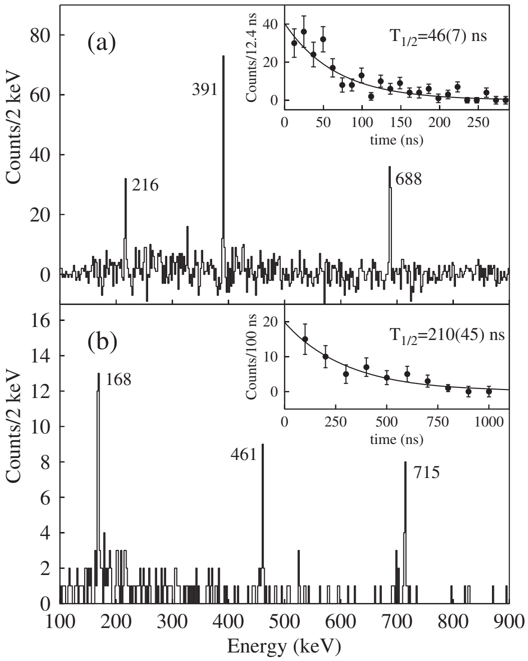

FIG. 2. Delayed γ rays in coincidence with (a) ^{136}Sn and (b) ^{138}Sn ions, obtained using high-resolution analogue timing electronics and digital electronics for better low-energy efficiency, respectively. The insets show the summed ion-γ time distributions for the three observed transitions of each isotopes.

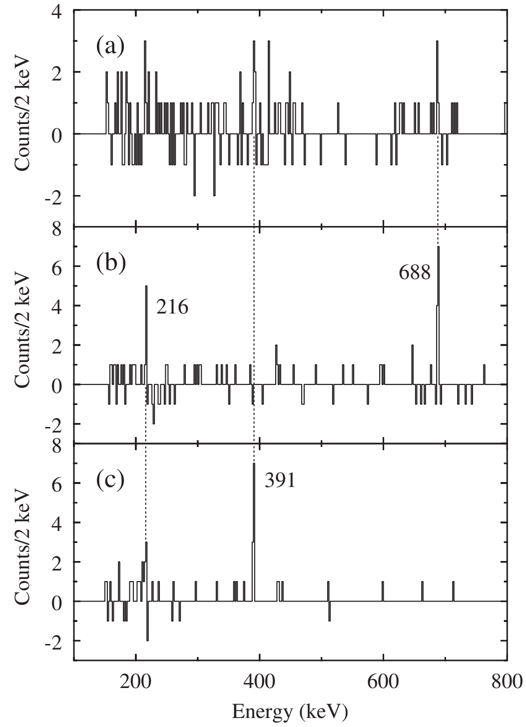

FIG. 3. Spectra of γ rays observed in coincidence with the (a) 216-keV, (b) 391-keV, and (c) 688-keV transitions in ^{136}Sn.

to the data yields a half-life of $T_{1/2} = 46(7)$ ns. This result is consistent with the average of the values obtained from fits of the individual decay curves of each of the three transitions. In the case of ^{138}Sn, three lines are clearly observed in the delayed-γ spectrum shown in Fig. 2(b), namely, at energies of 168, 461, and 715 keV. However, a lack of statistics did not allow γ-γ coincidences to be performed. Because of the limited statistics, only a common decay time could be determined via a least-squares fit to the summed time spectra shown in the inset of Fig. 2(b), resulting in a half-life of $T_{1/2} = 210(45)$ ns. The measured γ-ray intensities, corrected for efficiency, and half-lives for the isomeric cascades observed in coincidence with ^{136,138}Sn are shown in Table I.

When comparing the delayed γ-ray spectra in Fig. 2, the number of detected γ rays differs by only a factor of ~10, though ~175 times more ^{136}Sn ions were identified than those of ^{138}Sn. The main reason for this is the different half-lives of the isomeric states and their consequent in-flight decay when traveling though the BigRIPS separator. The flight time through the BigRIPS separator is ~640 ns, and this corresponds to ~10 half-lives of the isomeric state of ^{136}Sn, in the projectile frame. Therefore, only ~0.1% of the isomeric ^{136}Sn ions reach the stopper still in an excited state. The high number of ^{136}Sn ions collected in this experiment (8.75×10^5) means that, despite the large fraction of in-flight decay, a significant number of delayed γ transitions could still be detected.

The proposed level schemes of ^{136,138}Sn and a partial one of the neighboring $N = 84$ isotope ^{134}Sn [8] are shown in Fig. 4, along with two shell-model predictions for these nuclei, which are described in more detail below. The spins and parities have been assigned in analogy with the same isomeric decay cascade in ^{134}Sn.

The first set of shell-model calculations presented in Fig. 4, labeled "vlk," are taken from Ref. [11]. Here, the realistic effective interaction was based on a charge-dependent Bonn (CD-Bonn) free N-N potential, renormalized following a parameter-free $V_{\text{low-}k}$ procedure [2]. The model space outside the ^{132}Sn core contained the $0h_{9/2}$,

TABLE I. Energies, relative intensities, and half-lives of the γ-ray transitions observed in delayed coincidence with implanted ^{136,138}Sn ions.

E_γ (keV)	I_γ (relative)	$T_{1/2}$ (ns)
	^{136}Sn	
216(1)	95(29)	30(10)
391(1)	111(20)	50(12)
688(1)	100(19)	50(12)
Sum		46(7)
	^{138}Sn	
168(1)	121(29)	
461(1)	83(31)	
715(1)	100(33)	
Sum		210(45)

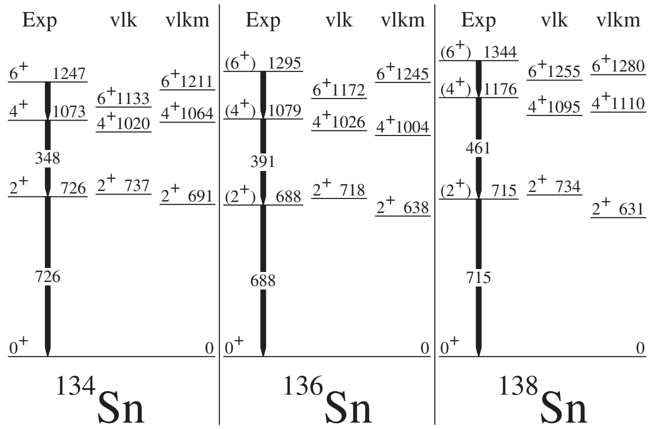

FIG. 4. Proposed level schemes of ^{136}Sn and ^{138}Sn, along with the neighboring even-even isotope ^{134}Sn [8] and the results of shell-model calculations using $V_{\text{low-}k}$ (vlk) [11] and modified $V_{\text{low-}k}$ (vlkm) interactions (see text for details).

$2p_{3/2}$, $2p_{1/2}$, $1f_{7/2}$, $1f_{5/2}$, and $0i_{13/2}$ neutron orbits. The effective single-particle energies were the experimental ones [11], and an effective neutron charge of e_ν=0.7e was used. These calculations reproduce well the experimentally determined level energies and $B(E2;6^+ \rightarrow 4^+)$ rate of ^{134}Sn, as previously mentioned in Ref. [11], along with the excited-state energies of ^{136,138}Sn reported in the present work. We have derived this effective interaction using the same methods as outlined above and calculated level energies and transition rates for ^{134,136,138}Sn, though using a slightly smaller e_ν=0.65e value, the same as in Ref. [12]. The results are shown in Fig. 5. Although the predicted and experimental $B(E2;6^+ \rightarrow 4^+)$ values agree for ^{138}Sn, those for ^{136}Sn differ by a factor of >5. Three other shell-model calculations, using realistic and empirical interactions, also failed to reproduce this value for ^{136}Sn and are off by at least a factor of 2 [12,13,24].

The observed near-constant energies of the 2^+, 4^+, and 6^+ states in ^{134,136,138}Sn, which vary by less than 10%,

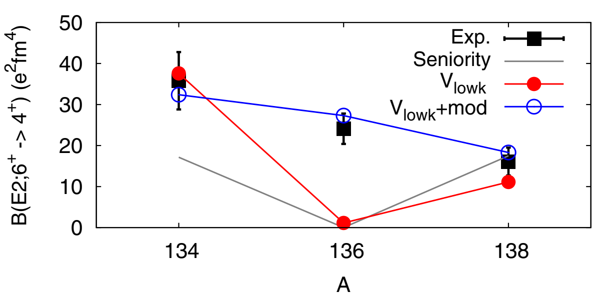

FIG. 5 (color online). Reduced transition rates for $6_1^+ \rightarrow 4_1^+$ transitions in $^{134-138}$Sn. In addition to the experimental values (black squares), results are reported for calculations using the realistic $V_{\text{low-}k}$ interaction (red filled circles), a pairing-modified $V_{\text{low-}k}$ interaction (blue open circles), and the diagonalization of only the $f_{7/2}$ orbit (grey curve), which corresponds to the pure seniority scheme.

are characteristic of a dominant seniority $\nu = 2$ scheme. The $B(E2)$ values of seniority-conserving transitions are expected to follow the shape of a symmetric positive parabola along a shell [10], as can be seen in Fig. 5. The results obtained with the realistic $V_{\text{low-}k}$ interaction are close to the seniority $\nu = 2$ pattern, having dominant $\nu = 2$ components of 96% and 84% in the 6^+ and 4^+ states wave functions of ^{136}Sn. However, the experimental data reveal substantial deviations from the pure $\nu f_{7/2}$-orbit seniority scheme for the $B(E2;6^+ \rightarrow 4^+)$ values for ^{134,136}Sn, indicating that the wave function of one or both of these states is more mixed.

The neutron-rich nuclei ^{70,76}Ni possess $\nu g_{9/2}^2$ 8_1^+ states with μs lifetimes, though these are much shorter lived in ^{72,74}Ni [25]. It has been postulated that $\nu = 4$ 6^+ levels drop below the 8_1^+ states in ^{72,74}Ni, giving alternative fast decay paths, destroying the μs isomerism [26]. States with mixed seniority are also responsible for the absence of μs isomers in maximally aligned $\pi g_{9/2}^{\nu}$ configurations, in some midshell $N = 50$ isotones [27]. One may pose the question as to whether an analogous situation arises in the midshell ^{136}Sn as the $\nu = 4$ 4_2^+ and 6_1^+ states are predicted to be approximately degenerate with the $V_{\text{low-}k}$ realistic interaction. The predicted value of $B(E2;6_1^+ \rightarrow 4_2^+) = 60$ e^2 fm^4, compared to the experimental value of $B(E2;6_1^+ \rightarrow 4^+) = 24(4)$ e^2 fm^4, seems incompatible with a decay to a pure $\nu = 4$ 4_2^+ state. If the $\nu = 4$ 4^+ state is close in energy to the $\nu = 2$ 4^+ level, these two states will mix and the transition rates will be somewhere between the two pure seniority ones. Calculations using realistic effective interactions had the $\nu = 4$ 6_2^+ levels sitting above the 8_1^+ states in $^{70-76}$Ni [28], and the lower energy of these $\nu = 4$ levels in ^{72,74}Ni has been proposed to be due to either reduced pairing or core polarization effects [26].

The influence of core polarization effects on the transition rates of the neutron-rich Sn nuclei has been examined in additional calculations with a partially open ^{132}Sn core, with the interactions derived in the same way as above and the single-hole energies taken from Ref. [29]. These allowed particle-hole excitations from the neutron $0h_{11/2}$ and proton $0g_{9/2}$ shells to the $N = 82$–126 and $Z = 50$–70 valence spaces, respectively. Effective polarization charges of 0.5e reproduce well the isomeric half-life of ^{134}Sn, showing that core excitations are now taken into account. However, these calculations fail to reproduce the observed $B(E2;6^+ \rightarrow 4^+)$ value for ^{136}Sn. This situation differs from the ^{208}Pb region where particle-hole excitations from the core, which account for effective three-body forces and effective two-body operators, allowed a coherent description of the $8^+ \rightarrow 6^+$ transition rates in ^{210,212,214,216}Pb [3].

The experimental $B(E2;6^+ \rightarrow 4^+)$ rate of ^{136}Sn can be reproduced by reducing the $\nu f_{7/2}^2$ diagonal and off-diagonal matrix elements by ~150 keV. This is the equivalent to reducing the neutron pairing strength and has the effect of lowering the 4_2^+ state by 250 keV, bringing it to within 150 keV of the 4_1^+ level, with the result that the 4_1^+ state now has mixed seniority (46% $\nu = 2$, 55% $\nu = 4$). Calculations using a realistic G-matrix interaction [12] similarly predict that the 4^+ state is 59% $\nu = 2$. The results with the modified interaction are shown in Figs. 4 and 5. The predicted transition rates for ^{134,136,138}Sn are now in line with the experimental ones. The agreement with the level energies is slightly improved, and binding-energy predictions for ^{134,135}Sn are not significantly degraded. Similar reductions in pairing have been applied to realistic effective interactions to produce better correlations with experimental data in both the $Z = 28$–50, $N = 28$–50 [30] and $Z = 28$–50, $N = 50$–82 [31] valence spaces. One notes that the two degenerate 6^+ states in ^{72,74}Ni are quoted as being relatively unmixed in the calculations of Ref. [30], whereas the close-lying 4^+ states in ^{136}Sn have almost equal $\nu = 2$, 4 components in the present work and Ref. [12]. Further theoretical work, beyond the scope of the present Letter, is required to determine the problems with the construction of realistic effective interactions, systematically present for semimagic, heavy nuclei.

In conclusion, three delayed γ rays each from ^{136,138}Sn have been observed and are the first reported γ-ray transitions in these very neutron-rich, semimagic nuclei. These cascades are proposed to originate from the decay of (6^+) isomeric states with dominant $f_{7/2}^2$ configurations, and the near-constant level energies in the decay cascade imply a seniority-2 coupling scheme. Realistic interactions do not reproduce the experimentally determined $B(E2; 6^+ \rightarrow 4^+)$ value of ^{136}Sn, even when core excitations are included. An empirical modification to the $\nu f_{7/2}^2$ matrix elements, equivalent to reduced pairing, generates a seniority-mixed 4_1^+ state, reproducing well all available experimental data. The present Letter provides essential information for the optimization and scrutinization of the neutron-neutron part of realistic interactions used in shell-model calculations far from stability in the very neutron-rich $Z = 50$–82, $N = 82$–126 valence space.

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